THREE DIMENSIONAL NUMERICAL SOLUTION FOR IMPEDANCE VOLTAGE OF POWER MULTI-WINDING AUTOTRANSFORMER

Alin DOLAN*, Grigore A. CIVIDJIAN*, Ivan YATCHEV, Gheorghe CALIN***, Dorin POPA*****

**University of Craiova, adolan@elth.ucv.ro, gcividjian@elth.ucv.ro*
***Technical University of Sofia, yatchev@tu-sofia.bg*
****ICMET Craiova, calin@icmet.ro, dpopa@icmet.ro*

Abstract – **In the paper, a leakage magnetic field of large power multi-winding autotransformer with regulating windings is analyzed using a 3D finite element method. Comparison with earlier 2D finite element method solution and experimental values is made.**

Keywords: *autotransformer, impedance voltage, 3D FEM.*

1. INTRODUCTION

The International Electrotechnical Vocabulary [1] define the impedance voltage of a multi-winding transformer for the principal tapping, related to a certain pair of windings as the voltage, required to be applied at rated frequency to the line terminals of one of the windings of a pair for a polyphase transformer, or to the terminals of such a winding for a single-phase transformer, to cause a current to flow through these terminals corresponding to the smaller of the rated power values of both windings of the pair, the terminals of the other winding of the pair being short-circuited and the remaining windings being open-circuited. The various values for the different pairs are normally related to the appropriate reference temperature. The impedance voltage at rated current is usually expressed as a percentage of the rated voltage of the winding to which the voltage is applied.

The short-circuit impedance of a pair of windings is defined, in the same vocabulary, as the equivalent star connection impedance, related to one of the windings, for given tapping and expressed in ohms per phase, at rated frequency, measured between the terminals of a winding when the other winding is short-circuited (the value is normally related to the appropriate reference temperature).

If in the case of principal tapping the impedance voltage of power transformers can be easy evaluated using the simple formulas, considering straight magnetic flux lines [2], in the case of other tapping of regulating winding consideration must be given to the magnetic field pattern.

2. BASIC EQUATIONS

Let w_1, w_2, w_3 and w_R be the numbers of turns of the three winding three-phase power autotransformer with regulating winding having respectively the powers S_1, S_2 and S_3 in MVA. The one-column powers will be:

$$S_i' = \frac{S_i}{3}, \quad i = \overline{1,3} \tag{1}$$

2.1. Primary and secondary winding

The secondary winding is connected to the median (principal) tapping of the regulating winding, so that the phase secondary voltages for median and marginal tapping will be respectively given by the vector [2], [3], [4]:

$$\vec{U}_2 = U_{2\text{phr}} \cdot \begin{bmatrix} 1 & \dfrac{w_2 + \dfrac{w_R}{2}}{w_2} & \dfrac{w_2 - \dfrac{w_R}{2}}{w_2} \end{bmatrix} \tag{2}$$

where:

$$U_{2\text{phr}} = \frac{U_1}{\sqrt{3}} \frac{w_2}{w_1 + w_2} \tag{3}$$

and U_1 is the primary rating voltage.

For the determination of the short-circuit parameters we will consider the system linear one and consequently, the magnetic field energy can be calculated for any arbitrary value of the primary line current I_{1e} (usually close to the primary rating current I_{1r}). For star connection the phase current will be the same and the corresponding secondary tapping currents result from the equality of the primary and secondary magnetomotive force (m.m.f.) and it will be given by the vector:

$$\vec{I}_{2c} = I_{1\text{eph}} \frac{w_1}{w_2} \cdot \begin{bmatrix} 1 & \dfrac{w_2}{w_2 + \dfrac{w_R}{2}} & \dfrac{w_2}{w_2 - \dfrac{w_R}{2}} \end{bmatrix} \tag{4}$$

where:

$$I_{1\text{eph}} = I_{1e} \tag{5}$$

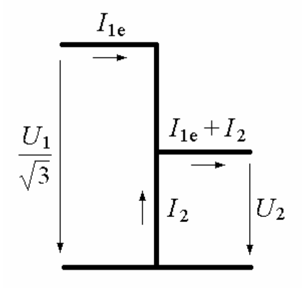

Figure 1: Autotransformer scheme.

The primary, secondary and regulating winding total cross-sections A_1, A_2 and A_R determine the corresponding current densities:

$$j_1 = w_1 \frac{I_{1eph}}{A_1}; \quad \vec{j}_2 = w_2 \frac{\vec{I}_{2c}}{A_2}; \quad \vec{j}_R = w_R \frac{\vec{I}_{2c}}{A_R} \tag{6}$$

Usually the primary and regulating windings are formed by two parallel-connected coils. In this case, in the above equations, the number of turn of one coil and the total cross-section of both coils must be considered.

Let W_{12} be the vector of magnetic field mean energy per phase, produced by the currents I_{1e} and I_{2c}, evaluated using the finite element method. The referred to primary winding short-circuit reactance will be:

$$\vec{x}_{k12\%} = 100 \cdot \frac{\vec{x}_{k12}}{x_{1r}} \ [\%] \tag{7}$$

where: $$\vec{x}_{k12} = \omega \cdot \frac{2\vec{W}_{12}}{I_{1e}^2} [\Omega], \quad x_{1r} = \frac{U_{1r}}{\sqrt{3}\, I_{1r}} \tag{8}$$

2.2. Primary and tertiary winding

Usually the tertiary winding rating power is smaller, so the short-circuit reactance will be referred to the tertiary winding rated line voltage U_{3r} and line current I_{3r}. This is also preferable if the tertiary winding has not several tapping. In this case the equivalent star connection rated impedance will be similar with the above:

$$x_{3r} = \frac{U_{3r}}{\sqrt{3}\, I_{3r}} \tag{9}$$

For delta connection of the tertiary winding, the phase currents for energy calculation are:

$$\vec{I}_{1c} = I_{3eph} w_3 \cdot \begin{bmatrix} \dfrac{1}{w_1 + w_2} & \dfrac{1}{w_1 + w_2 + \dfrac{w_R}{2}} & \dfrac{1}{w_1 + w_2 - \dfrac{w_R}{2}} \end{bmatrix} \tag{10}$$

where: $$I_{3eph} = \frac{I_{3e}}{\sqrt{3}} \tag{11}$$

The corresponding current densities are:

$$\vec{j}_1 = w_1 \frac{\vec{I}_{1c}}{A_1}; \quad \vec{j}_2 = w_2 \frac{\vec{I}_{1c}}{A_2}; \quad j_3 = w_3 \frac{I_{3eph}}{A_3}; \quad \vec{j}_R = w_R \frac{\vec{I}_{1c}}{A_R} \tag{12}$$

Let W_{13} be the vector of magnetic field energy (per phase), produced by the currents I_{3e} and I_{1c}, evaluated using the finite element method. The referred to tertiary winding (equivalent to star connection) short-circuit reactance will be:

$$\vec{x}_{k13\%} = 100 \cdot \frac{\vec{x}_{k13}}{x_{3r}} \ [\%] \tag{13}$$

where: $$\vec{x}_{k13} = \omega \cdot \frac{2\vec{W}_{13}}{I_{3e}^2} [\Omega], \quad x_{3r} = \frac{U_{3r}}{\sqrt{3}\, I_{3r}} \tag{14}$$

2.3. Secondary and tertiary winding

The determination of the short-circuit reactance for the secondary and tertiary windings is similar with the previous case. The secondary and regulating winding currents will be:

$$\vec{I}_{2c} = I_{3eph} w_3 \cdot \begin{bmatrix} \dfrac{1}{w_2} & \dfrac{1}{w_2 + \dfrac{w_R}{2}} & \dfrac{1}{w_2 - \dfrac{w_R}{2}} \end{bmatrix} \tag{15}$$

where: $$I_{3eph} = \frac{I_{3e}}{\sqrt{3}} \tag{16}$$

The current densities:

$$\vec{j}_2 = w_2 \frac{\vec{I}_{2c}}{A_2}; \quad j_3 = w_3 \frac{I_{3eph}}{A_3}; \quad \vec{j}_R = w_R \frac{\vec{I}_{2c}}{A_R} \tag{17}$$

Let W_{23} be the vector of magnetic field energy, produced by the currents I_{3e} and I_{2c}, evaluated using the finite element method. The referred to tertiary winding (equivalent to star connection) short-circuit reactance will be:

$$\vec{x}_{k23\%} = 100 \cdot \frac{\vec{x}_{k23}}{x_{3r}} \ [\%] \tag{18}$$

where: $$\vec{x}_{k23} = \omega \cdot \frac{2\vec{W}_{23}}{I_{3e}^2} [\Omega], \quad x_{3r} = \frac{U_{3r}}{\sqrt{3}\, I_{3r}} \tag{19}$$

3. MAGNETIC FIELD ENERGY EVALUATION

The magnetic field problem is solved using ANSYS® program for static magnetic field [5], [6].

Due to the relatively small size of the coil conductors, is neglect the skin effect in the conductors and in the screens. Consequently, the coil conductivity is taken equal to zero and the frequency is also considered zero.

3.1. Numerical computation

For analysis of the 3D static magnetic field of the autotransformer, the MVP-edge based formulation implemented in ANSYS® program has been employed.

The MVP-edge based formulation associates degrees of freedom with element edges rather than element nodes. It is often considered as better than the MVP-nodal based formulation in the cases of presence of media of different properties [6].

The numerical results of the 3-D static analysis have been obtained using ANSYS® program, for each pairs of the windings of the 400/400/80 MVA power autotransformer for 400/231/22 kV.

For automation of the numerical computation, command files have been created using APDL (ANSYS Parameter Design Language). This allows multiple runs to be executed easily and changing any of the parameters is carried out only by changing a line in the command file.

The mesh was realized using tetrahedral elements. The eighth part of model was analysed, an eight-time reduction of the nodes number being obtained. The number of nodes varies in range 200.000 - 250.000, being limited by hardware resources.

The computations were run on a PC with 512 MB RAM and 2.4 GHz frequency processor, the execution time for the maximum number of nodes reaching the value of four hours of work.

3.2. Boundary conditions

In the analysed domain, the flux normal conditions have been considered for the borders, corresponding to the transformer ferromagnetic tank and for the horizontal interior plane of symmetry.

For the two verticals interiors planes of symmetry, the flux parallel conditions have been imposed.

In the next tables, the apparent current densities, the magnetic field energies per phase, computed by 3D finite element method and the values of short-circuit reactance are given for the principal, plus and minus tappings. The values are compared with the corresponding experimental values of the impedance voltage and with earlier 2D finite element method results, obtained using axisymmetric solution of FEMM program [4].

Using the visualization facilities offered by ANSYS® program, the Figure 2 shows the 3D symmetry-plane perspective of the model with associated mesh.

The magnetic flux density distribution on the borders and symmetry planes is shown in Figure 3, corresponding to the case of primary-secondary windings short-circuit test at minus tapping of the regulating winding.

Tapping			0	+	-
	I_{1e}	[A]	577.35	577.35	577.35
	j_1	[A/mm^2]	0.799	0.799	0.799
	j_2	[A/mm^2]	-0.922	-0.749	-1.198
	j_R	[A/mm^2]	0	-0.871	1.393
	x_{k12exp}	[Ω]	40.410	29.560	82.680
2D	W_{12}	[J]	21766	15314	43948
	x_{k12}	[Ω]	41.028	28.866	82.840
	x_{k12}	[%]	10.257	7.217	20.710
	Er.	[%]	-1.53	2.33	-0.19
3D	W_{12}	[J]	21217	15353	43344
	x_{k12}	[Ω]	39.994	28.941	81.702
	x_{k12}	[%]	9.998	7.235	20.425
	Er.	[%]	1.03	2.10	1.18

Table 1: Primary-secondary windings short-circuit test.

Tapping			0	+	-
	I_{1e}	[A]	2099.47	2099.47	2099.47
	j_3	[A/mm^2]	-2.045	-2.045	-2.045
	j_2	[A/mm^2]	0.252	0.222	0.291
	j_1	[A/mm^2]	0.16	0.141	0.184
	j_R	[A/mm^2]	0	0.259	-0.338
	x_{k31exp}	[Ω]	0.546	0.618	0.522
2D	W_{31}	[J]	3768	4372	3556
	x_{k31}	[Ω]	0.537	0.623	0.507
	x_{k31}	[%]	8.878	10.301	8.379
	Er.	[%]	1.63	-0.85	2.89
3D	W_{31}	[J]	3798	4370	3600
	x_{k31}	[Ω]	0.541	0.623	0.513
	x_{k31}	[%]	8.949	10.298	8.482
	Er.	[%]	0.84	-0.81	1.69

Table 2: Tertiary-primary windings short-circuit test.

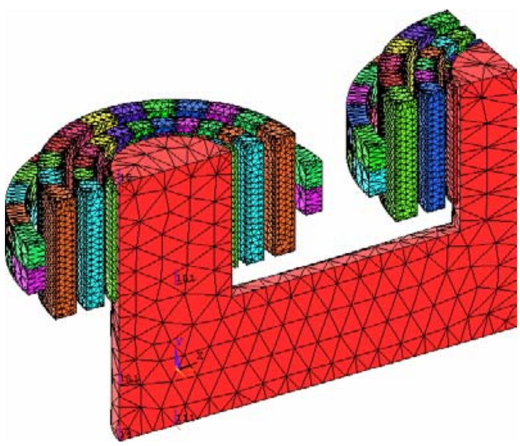

Figure 2: Mesh model perspective.

Tapping			0	+	-
I_{3e}		[A]	2099.47	2099.47	2099.47
j_3		[A/mm^2]	-2.045	-2.045	-2.045
j_2		[A/mm^2]	0.436	0.355	0.567
j_R		[A/mm^2]	0	0.412	-0.659
x_{k32exp}		[Ω]	0.368	0.472	0.506
2D	W_{32}	[J]	2512	3296	3850
	x_{k32}	[Ω]	0.358	0.470	0.549
	x_{k32}	[%]	5.919	7.766	9.071
	Er.	[%]	2.69	0.46	-8.46
3D	W_{32}	[J]	2611	3372	3955
	x_{k32}	[Ω]	0.372	0.481	0.564
	x_{k32}	[%]	6.152	7.946	9.319
	Er.	[%]	-1.14	-1.85	-11.43

Table 3: Tertiary-secondary windings short-circuit test.

4. CONCLUSIONS

1. In the case of regulating windings, the impedance voltage cannot more be accurately determined using classical methods and finite element method must be used.
2. At commercial frequency the transformer leakage magnetic flux can be well approximated with the static (zero frequency) flux.
3. The numerical 3D FEM computed values of the impedance voltage, of the studied 400 MVA autotransformer, agree with the experimental ones with a precision less than 3 %, with one exception of almost 11 %, for minus tapping of tertiary and secondary windings. The same results and exception (of about 8 %) have been met in 2D FEM analyses, using an axisymmetric solution.
4. The 3D approach requires much more hardware resources than the 2D approach for obtaining the same precision but it is preferable in the cases of nonsymmetrical configurations.

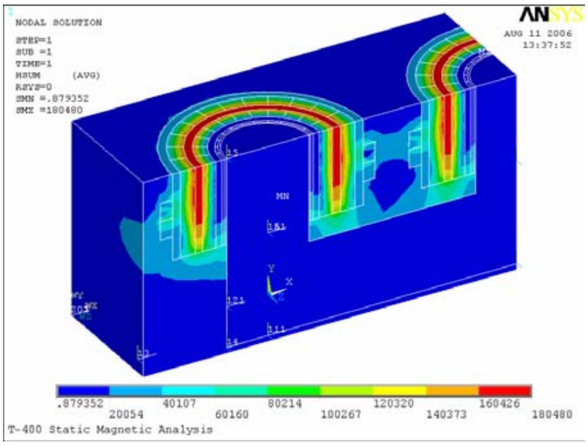

Figure 3: Magnetic field distribution for primary-secondary windings short-circuit test at minus tapping of the regulating winding.

References

[1] Electricity, Electronics and Telecommunications, *IEC Multilingual Dictionary*, vol. 1, Elsevier, Amsterdam, New-York, Tokyo, Oxford, 1992.

[2] Г.Н. Петров, *Электрические машины ч. 1*, Трансформаторы, ГЭИ, Москва, 1956.

[3] П.М. Тихомиров, *Расчет трансформаторов*, Энергоатомиздат, Москва, 1986.

[4] G.A. Cividjian, G. Calin, D. Popa, A. Dolan, *Impedance voltage of power multi-winding autotransformer,* XIV-th International Symposium on Electrical Apparatus and Technologies, SIELA 2005, Plovdiv, Bulgaria, vol. I, 2005, pp. 39-44.

[5] A. Dolan, I. Yatchev, K. Hinov, *Static force characteristics of a plunger type electromagnet,* International PhD Seminar - Numerical Field Computation and Optimization in Electrical Engineering, Ohrid, Macedonia, 2005, pp. 67-71.

[6] *ANSYS Documentation - ANSYS, Inc. Theory Reference*.